APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

DUOBINARY RECEIVER

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DUOBINARY RECEIVER

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to optical communication equipment and, more specifically, to equipment for processing optical duobinary signals.

Description of the Related Art

Duobinary signaling was introduced in the 1960s and since then has found numerous applications in communication systems. The principle of duobinary signaling is explained, for example, in an article by A. Lender that appeared in IEEE Transactions on Communications and Electronics, Vol. 82 (May, 1963), pp. 214-218, the teachings of which are incorporated herein by reference. Briefly, duobinary signaling uses three signal levels, for example, "+1", "0", and "−1". A signal corresponding to one of these levels (i.e., a duobinary symbol) is transmitted during each signaling interval (time slot). A duobinary signal is typically generated from a corresponding binary signal using certain transformation rules. Although both signals carry the same information, the bandwidth of the duobinary signal may be reduced by a factor of 2 compared to that of the binary signal. In addition, the duobinary signal may be constructed such that it has certain inter-symbol correlation (ISC) data, which can be used to implement an error-correction algorithm at the receiver.

A number of different transformations have been proposed for constructing a duobinary sequence, b_k, from a corresponding binary sequence, a_k, where $k = 1, 2, 3, \ldots$ One such transformation described in the above-cited Lender article is as follows. For any particular $k = m$, when $a_m = 0$, $b_m = 0$. When $a_m = 1$, b_m equals either +1 or −1, with the polarity of b_m determined based on the polarity of last non-zero symbol b_{m-i} preceding b_m, where i is a positive integer. More specifically, when i is odd, the polarity of b_m is the same as the polarity of b_{m-i}; and, when i is even, the polarity of b_m is the opposite of the polarity of b_{m-i}. Due to the properties of this transformation, the duobinary sequence has no transitions between the "+1" and "−1" levels in successive time slots. Only transitions between (i) "0" and "+1" and (ii) "0" and "−1" levels can occur. Reconstruction of a_k from a known b_k is relatively straightforward. More specifically, when $b_m = \pm 1$, $a_m = 1$; and, when $b_m = 0$, $a_m = 0$.

In optical communication systems, duobinary encoding is typically implemented using phase modulation of a carrier optical beam disclosed in U.S. Patent No. 5,867,534, the teachings of which are incorporated herein by reference. More specifically, for the "0" bit, substantially no light is transmitted. However, the "+1" and "−1" bits are transmitted as light having +E and −E electric fields, respectively, where opposite polarities of the electric field correspond to a relative

optical phase shift of 180 degrees. While an optical beam modulated in this manner is a three-level signal in terms of the electric field, it is a two-level signal in terms of the optical power. Based on this property of duobinary signals, a "binary" receiver may be adapted to serve as a duobinary receiver. A conventional binary receiver simply measures optical power. Since both "+1" and "−1" duobinary states correspond to light "on", a binary receiver can convert optical duobinary input signals into electrical output signals by measuring optical power. However, it would be desirable to have a specialized duobinary receiver, which, when deployed in a communication system in place of a regular binary receiver, would improve the system performance using advantages of optical duobinary coding.

SUMMARY OF THE INVENTION

Problems in the prior art are addressed, in accordance with the principles of the present invention, by an optical receiver adapted to process an optical duobinary signal received over a transmission link in an optical communication system. In one embodiment, the receiver has an optical-to-electrical signal converter coupled to a decoder. The decoder processes an electrical signal generated by the converter to generate a bit sequence corresponding to the optical signal. To generate a bit value, the decoder integrates the electrical signal using a sampling window and compares the integration result with a decision threshold value. In one configuration, the width of the sampling window and the decision threshold value are selected based on the eye diagram and noise distribution function, respectively, corresponding to the optical signal. Advantageously, embodiments of the present invention improve overall back-to-back (i.e., source-to-destination) system performance, e.g., by reducing the level of optical power corresponding to a selected bit error rate value in an optically pre-amplified receiver.

According to one embodiment, the present invention is a method of signal processing, comprising: converting an optical signal into an electrical signal having an amplitude corresponding to optical power of the optical signal; and sampling the electrical signal using a sampling window to generate a bit sequence corresponding to the optical signal, wherein: the sampling window has a width; the electrical signal has a series of waveforms comprising first and second pluralities of waveforms, wherein each waveform of the first plurality represents a binary "0" and each waveform of the second plurality represents a binary "1"; each waveform is integrated over the sampling window width to generate a corresponding bit value; and the sampling window width is selected to reduce contribution of the second plurality of waveforms into integration results corresponding to the first plurality of waveforms.

According to another embodiment, the present invention is an optical receiver, comprising: a signal converter adapted to convert an optical signal into an electrical signal having an amplitude corresponding to optical power of the optical signal; and a decoder coupled to the

signal converter and adapted to (i) sample the electrical signal using a sampling window and (ii) generate a bit sequence corresponding to the optical signal, wherein: the sampling window has a width; the electrical signal has a series of waveforms comprising first and second pluralities of waveforms, wherein each waveform of the first plurality represents a binary "0" and each

5   waveform of the second plurality represents a binary "1"; each waveform is integrated over the sampling window width to generate a corresponding bit value; and the sampling window width is selected to reduce contribution of the second plurality of waveforms into integration results corresponding to the first plurality of waveforms.

10   BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and benefits of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

Fig. 1 shows a block diagram of a representative optical communication system adapted to

15   use optical duobinary coding;

Fig. 2 shows a block diagram of a representative receiver that can be used in the system of Fig. 1;

Figs. 3A-D graphically illustrate representative distortions in optical binary and duobinary signals due to dispersion effects in an optical link;

20   Figs. 4A-B show a representative eye diagram of a (10 Gb/s) duobinary signal and the corresponding noise distribution function, respectively, in the system of Fig. 1;

Fig. 5 shows a block diagram of a receiver that can be used in the system of Fig. 1 according to one embodiment of the present invention; and

Figs. 6-8 graphically compare performance characteristics of different configurations of

25   the system shown in Fig. 1.

DETAILED DESCRIPTION

Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included

30   in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

Fig. 1 shows a block diagram of a representative optical communication system **100** adapted to use optical duobinary coding. System **100** has a duobinary transmitter **102** coupled to a

35   receiver **108** via a transmission link having an optical fiber **104** and one or more optical amplifiers **106**. Transmitter **102** receives a binary sequence, a_k, and generates a corresponding optical

duobinary signal, $A(t)$, which is received as signal $S(t)$ at receiver **108**. Compared to signal $A(t)$, signal $S(t)$ may have distortions due to chromatic dispersion (CD) and polarization mode dispersion (PMD) in fiber **104** and/or amplification noise in amplifier **106**. Receiver **108** converts optical signal $S(t)$ into a corresponding electrical signal and processes that signal to generate

5   binary sequence a'_k, corresponding to sequence a_k.

Descriptions of duobinary transmitters that can be used as transmitter **102** can be found, for example, in the following articles: (1) J. M. Gene et al., IEEE Photonics Technology Letters, 2002, vol. 14, p. 843; (2) W. Kaiser et al., IEEE Photonics Technology Letters, 2001, vol. 13, p. 884; (3) H. Kim and C.X. Yu, IEEE Photonics Technology Letters, 2002, vol. 14, p. 1205; and (4)

10   H. Bissessur, Electronics Letters, 2001, vol. 37, p. 45, the teachings of all of which are incorporated herein by reference.

Fig. 2 shows a block diagram of a receiver **200** that can be used as receiver **108** in system **100**. Receiver **200** has an optical-to-electrical (O/E) signal converter (e.g., a photodiode) **206** that converts optical signal $S(t)$ into electrical signal $S'(t)$ whose amplitude is proportional to the optical

15   power of signal $S(t)$. A decoder **208** samples signal $S'(t)$, e.g., by integrating it over a fraction of each bit length termed a "sampling window," and compares the integration result with a decision threshold value. Based on the comparison, decoder **208** outputs either digital "1" or digital "0" for sequence a'_k. Optimal performance of decoder **208** is achieved when both the width of the sampling window and the decision threshold value are appropriately selected to minimize the

20   number of decoding errors arising from the presence of distortions and noise in signal $S'(t)$.

Figs. 3A-D graphically illustrate representative distortions in optical binary and duobinary signals due to dispersion effects in an optical link, e.g., fiber **104** in system **100**. However, it has to be noted that the waveforms shown in Figs. 3A-D represent a simplified graphical depiction of actual waveforms that may be used in system **100**. Referring to Figs. 3A-B, a "101" binary

25   sequence is mapped onto the optical domain as "+E, 0, +E" in optical binary NRZ (non-return-to-zero) coding (Fig. 3A) and as "+E, 0, –E" in optical duobinary coding (Fig. 3B). One effect of dispersion is to broaden optical pulses as shown in Figs. 3C-D. As indicated in Fig. 3C, broadened optical pulses of the NRZ waveform interfere constructively in the area corresponding to the optical "0," thereby making it difficult to properly decode said "0" at the receiver.

30   However, as indicated in Fig. 3D, broadened optical pulses of the duobinary waveform interfere destructively in the area corresponding to the optical "0," which may preserve a relatively narrow "valley" between two optical "ones" and improve chances of properly decoding said "0" at the receiver.

Figs. 4A-B show a representative eye diagram of (10 Gb/s) signal $S(t)$ and the

35   corresponding noise distribution function, respectively, in system **100**. Referring to Fig. 4A, the eye diagram shows different waveforms that may be transmitted in system **100** over a time interval

corresponding to two bit periods. For example, waveform **402** having a relatively broad pulse centered at about 100 ps corresponds to a "010" binary sequence. Similarly, waveform **404** having a relatively narrow valley centered at about 100 ps corresponds to a "101" binary sequence. One skilled in the art will appreciate that other waveforms shown in Fig. 4A correspond to "111",

5   "110", "100", "000", "001", and "011" bit sequences. Referring to Fig. 4B, at the "mark" level (i.e., the level corresponding to binary "1"), the total noise is dominated by the spontaneous beat noise in optical amplifiers, e.g., amplifiers **106** (Fig. 1). At the "space" level (i.e., the level corresponding to binary "0"), the total noise is dominated by thermal noise. However, in the region between the mark and space levels, there usually exists a region of relatively low noise

10   probability corresponding to a minimum of the noise distribution function.

As already indicated above, to configure decoder **208**, one has to select the width of the sampling window and a decision threshold value. Figs. 4A-B graphically illustrate these selections made in accordance with prior-art processing methods and one embodiment of the present invention. More specifically, sampling windows A and B correspond to prior-art

15   configurations of decoder **208** and sampling window D corresponds to a novel configuration of the decoder according to one embodiment of the present invention.

In a typical prior-art configuration, the sampling window has a relatively large width, e.g., greater than 30% of the bit length. One consideration for choosing a relatively large width value is that longer integration times typically reduce decoding errors due to noise averaging. It is

20   generally believed that setting a relatively narrow sampling window will reduce the benefits of noise averaging and detrimentally affect performance of receiver **200**. However, for signals affected by dispersion, using a relatively wide sampling window increases decoding errors due to wrong interpretation of zeros in "101" binary fragments (see Figs. 3C-D). For similar reasons, analogous decoding errors may be caused by dispersion-free signals utilizing relatively large duty-

25   cycle values, e.g., greater than 1 (see Fig. 4A). As discussed below, attempts to reduce said errors by simply adjusting the decision threshold value are largely ineffective.

Referring again to Fig. 4A, waveform **404** has a relatively narrow valley between two relatively broad pulses. Sampling windows A and B have different decision threshold values but identical widths. As can be seen in Fig. 4A, when sampling window A is used, the integration

30   result corresponding to waveform **404** may have a relatively large contribution from the part of the waveform corresponding to the trailing edge of the preceding optical "1" and the part of the waveform corresponding to the leading edge of the next optical "1". This increases the probability of decoding errors because, even in the absence of noise, the gap between the decision threshold value and the integration result of waveform **404** is relatively narrow. The contribution of noise

35   may then easily cause the integration result to overshoot the decision threshold value, thereby causing a decoding error for waveform **404**. On the other hand, raising the decision threshold

value to that of sampling window B will narrow the gap between the decision threshold value and the noise-free integration result of waveform **402**. The contribution of signal spontaneous beat noise (Fig. 4B) may then cause the integration result to undershoot the decision threshold value, thereby causing a decoding error for waveform **402**. In either case, the number of decoding errors is relatively large.

As will be further demonstrated below, contrary to the general expectations, the number of decoding errors in decoder **208** can be reduced for duobinary signals by decreasing the sampling window width and properly aligning said window with respect to the waveforms of the signal. For example, when sampling window D is used for waveform **404** (Fig. 4A), the contribution into the integration result from the part of the waveform corresponding to the trailing edge of the preceding optical "1" and the part of the waveform corresponding to the leading edge of the next optical "1" is significantly reduced compared to the configuration where window A or window B is used. This decreases the probability of decoding errors because the gap between the decision threshold value and the integration result of noise-free waveform **404** can now be relatively large. Consequently, it becomes more difficult for the contribution of noise to cause the integration result to overshoot the decision threshold value, which reduces the number of decoding errors. In addition, the decision threshold value itself may now be selected to correspond to the "low noise" region without incurring a relatively large penalty from the trailing/leading edges of the adjacent optical "ones." As a result, the overall contribution of noise into the integration results is reduced. Furthermore, the gap between the decision threshold value and the noise-free integration result of waveform **402** becomes relatively wide. Therefore, it becomes more difficult for the contribution of signal spontaneous beat noise (Fig. 4B) to cause said integration result to undershoot the decision threshold value, which further reduces the number of decoding errors.

In one configuration, the width of sampling window D for decoder **208** is selected based on an eye diagram similar to that shown in Fig. 4A. For example, when the duty cycle value or dispersion caused optical pulse broadening is relatively large, the "zero" valley of waveforms analogous to waveform **404** becomes relatively narrow. In accordance with the principles of the present invention, the sampling window width is selected to be even narrower than the "zero" valley, e.g., as illustrated in Fig. 4A. In one implementation, the width of sampling window D is less than about 25% of the bit length or preferably fixed at about 10% of the bit length.

Fig. 5 shows a block diagram of a receiver **500** that can be used as receiver **108** in system **100** according to one embodiment of the present invention. Similar to receiver **200** of Fig. 2, receiver **500** is adapted to receive optical duobinary signal $S(t)$ and convert it into a corresponding binary sequence a'_k. Receiver **500** has an O/E signal converter **506** that is similar to converter **206** of receiver **200**. A decoder **508** samples signal $S'(t)$ generated by converter **506**, e.g., using a configuration corresponding to sampling window D of Fig. 4A. To provide an appropriate time

reference for aligning the sampling window, receiver **500** has a clock recovery circuit **502** and a

clock multiplier **504**. Circuit **502** processes signal $S'(t)$ to generate a first clock signal

synchronized with signal $S'(t)$. Clock multiplier **504** multiplies the frequency of the first clock

signal and generates a second clock signal applied to decoder **508**. In a representative

5   configuration of receiver **500**, the second clock signal has a frequency value four times that of the

first clock. Decoder **508** then uses clock pulses to align sampling window D with respect to signal

$S'(t)$. In addition, the width of the sampling window may be selected based on the inter-pulse

separation in the second clock signal. One skilled in the art will appreciate that other

synchronization techniques may similarly be used.

10   Figs. 6-8 graphically compare performance characteristics of two different configurations

of system **100**. More specifically, Figs. 6-7 show dispersion tolerance at bit error rate (BER) of

10^{-3}, and Fig. 8 shows dependence of BER on the power of signal $S(t)$. In both configurations,

transmitter **102** is a transmitter based on a Mach-Zehnder modulator operating at a bit rate of 10

Gb/s. In configuration I, receiver **108** is receiver **500** (Fig. 5), wherein the second clock signal has

15   a frequency value corresponding to four times the bit rate. In configuration II, receiver **108** is

receiver **200** (Fig. 2), which has (i) a sampling window width corresponding to that of sampling

windows A and B shown in Fig. 4 and (ii) a decision threshold value set at about 25% of the mark

level.

          Referring to Fig. 6, for system **100**, configuration I provides optical signal-to-noise

20   (OSNR) gain of about 1 dB with respect to configuration II for chromatic dispersion values

between 0 and about 4000 ps/nm. Referring to Fig. 7, configuration I consistently outperforms

configuration II for PMD-affected signals having differential group delay (DGD) values between 0

and about 50 ps. On average, configuration I improves PMD tolerance by about 20%. Referring

to Fig. 8, for a selected bit error rate value, configuration I provides substantial gain over

25   configuration II in terms of the optical power at the receiver. For example, for a BER value of 10^{-6}, configuration I lowers the coresponding optical power by about 3 dB with respect to that in

configuration II. In summary, embodiments of the present invention improve dispersion tolerance

and reduce optical power corresponding to a selected BER value in duobinary transmission

systems, thereby improving overall back-to-back (i.e., source-to-destination) performance of such

30   systems.

          While this invention has been described with reference to illustrative embodiments, this

description is not intended to be construed in a limiting sense. Although the present invention is

described with reference to duobinary signals, it can also be used for processing other types of

signals, e.g., high-duty-cycle binary NRZ signals. Various modifications of the described

35   embodiments, as well as other embodiments of the invention, which are apparent to persons

skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

Although the steps in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those steps, those steps are not necessarily intended to be limited to being implemented in that particular sequence.

The present invention may be implemented as circuit-based processes, including possible implementation on a single integrated circuit. As would be apparent to one skilled in the art, various functions of circuit elements may also be implemented as processing steps in a software program. Such software may be employed in, for example, a digital signal processor, micro-controller, or general-purpose computer.